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Probing Dynamic Response to Temperature Changes in Berea Sandstone using Acoustic Time-of-Flight and Resonant Ultrasound Spectroscopy

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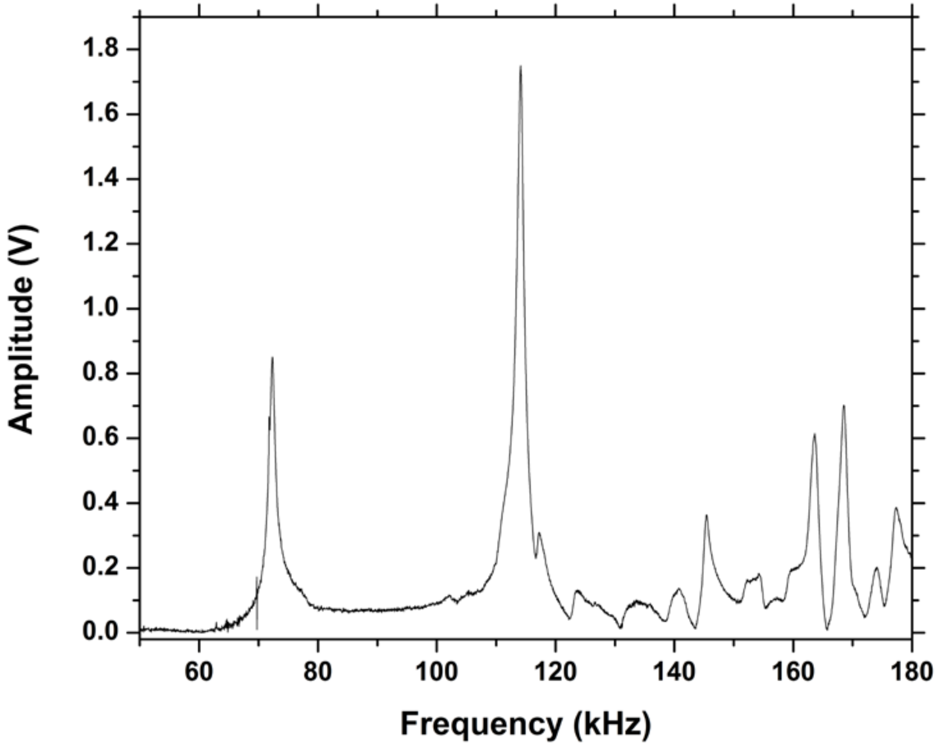
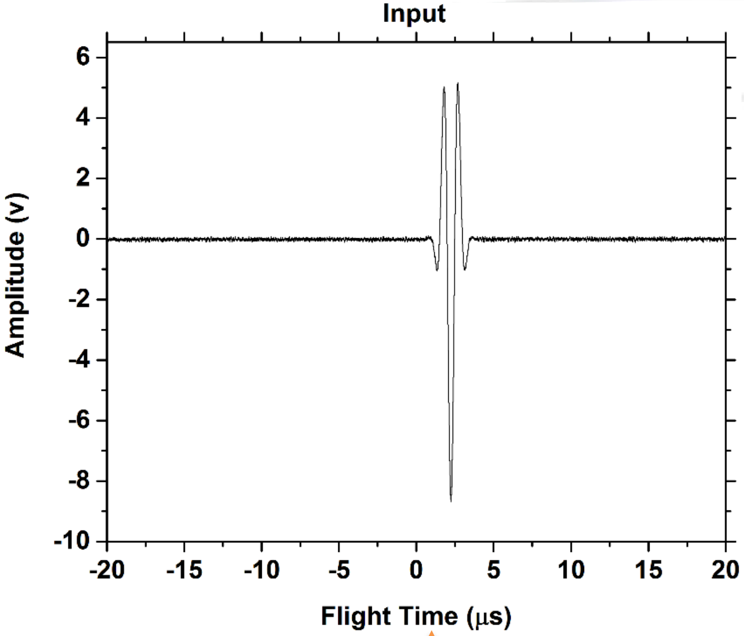
Background

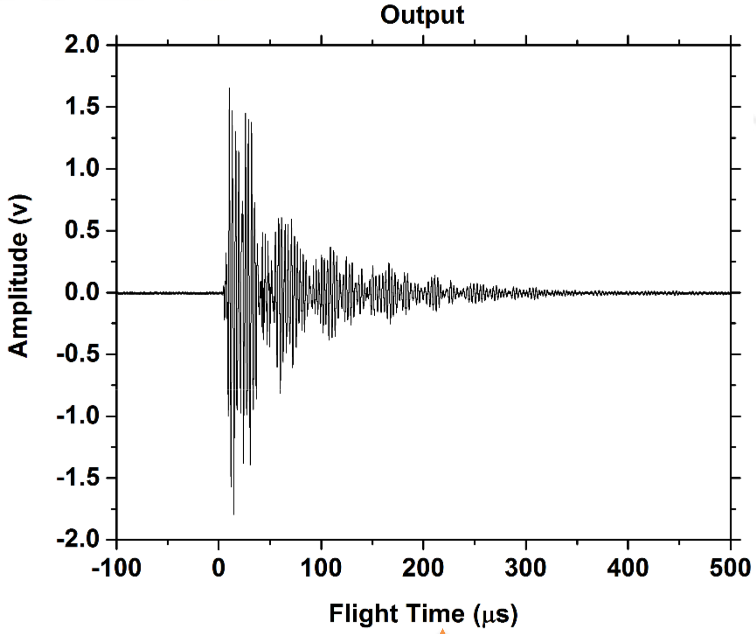
- Current research is focused on the mechanical properties of sandstones in extreme conditions
- Relevant to the oil & gas industries, earth sciences
- Acoustic techniques were used due to high accuracy (ref 1)
- In particular, RUS and Pitch-Catch techniques



[1]Migliori, A., and J. D. Maynard (2005), Implementation of a modern resonant ultrasound spectroscopy system for the measurement of the elastic moduli of small solid specimens. *Review of Scientific Instruments, 76*(12), Vol.76(12).

Experimental



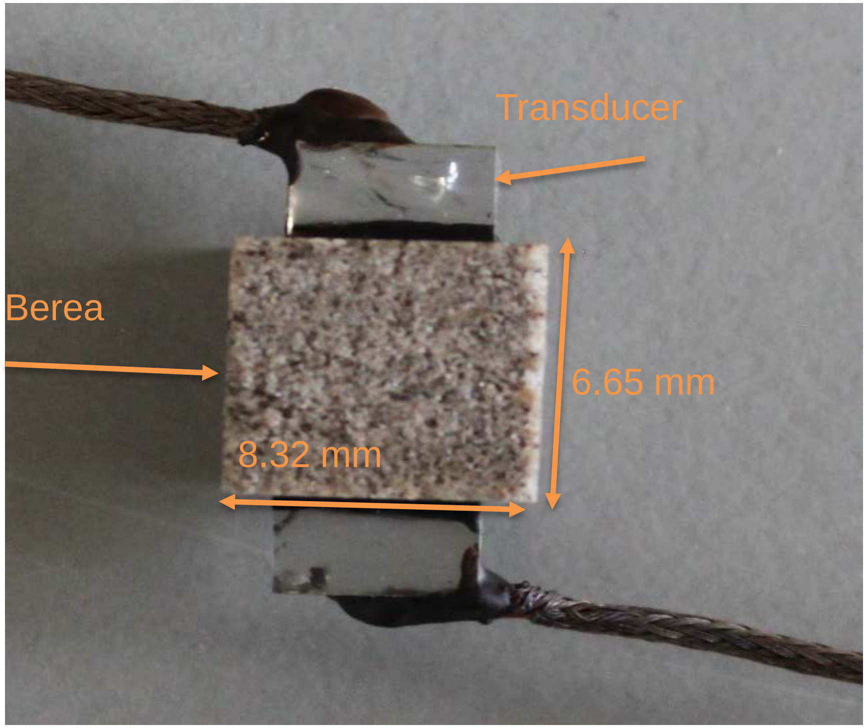


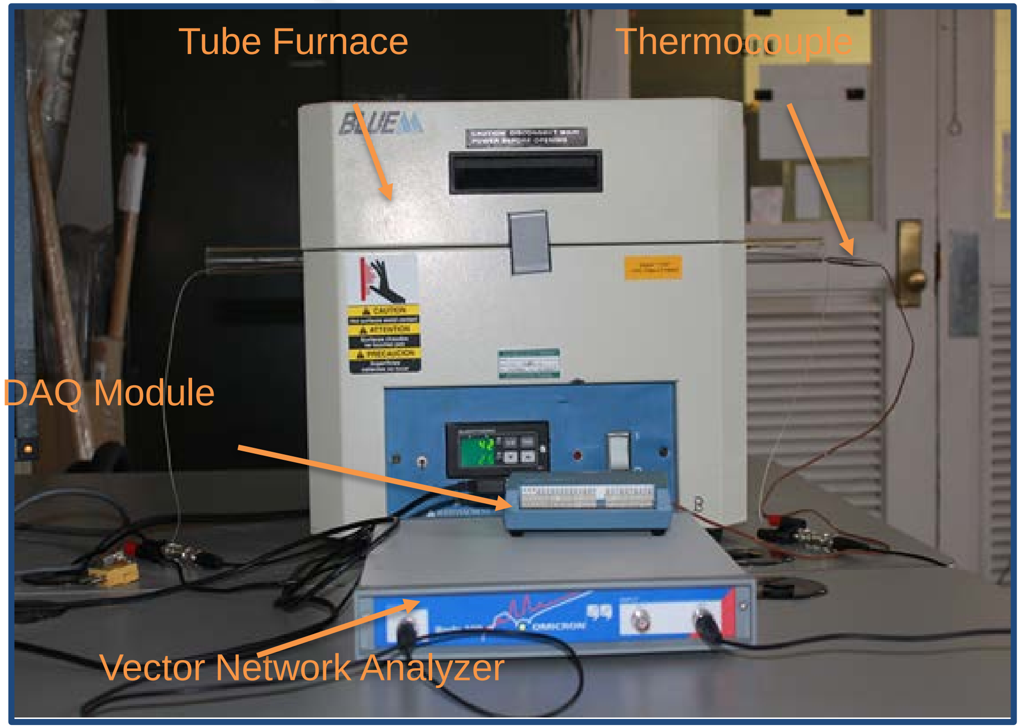
Experimental

- Resonant Ultrasound Spectroscopy (RUS) is a swept-frequency technique
- Measures resonances of the material
- Uses transducers positioned opposite of each other, generally corner mounted to the sample
- Samples are usually cut to rectangular parallelepipeds or cylinders
- The quality factor (Q) of the material determines how sharp and easily resolvable the resonant frequencies are
- Berea sandstone has a low Q (~200)
- RUS solves an inverse problem – using resonant frequencies, mass density, sample dimensions, to determine elastic moduli

```
 LANL RPRcode Ver. 6.0

free moduli are  c11, c44
using 14 order polynomials    mass=  1.0720 gm  rho= 2.067 gm/cc

 n      fex       fr        %err   wt    k    i     df/d(moduli)
  1 0.072590 0.072938   0.48 0.00  4    1   0.00  1.00
  2 0.000000 0.097088   0.00 0.00  6    2   0.21  0.79
  3 0.099000 0.100617   1.63 0.00  4    2   0.00  1.00
  4 0.100000 0.103570   3.57 0.00  7    2   0.31  0.69
  5 0.109022 0.109047   0.02 1.00  3    2   0.04  0.96
  6 0.117573 0.114288  -2.79 0.00  6    3   0.61  0.39
  7 0.117573 0.118522   0.81 1.00  1    2   0.27  0.73
  8 0.117000 0.120212   2.75 0.00  2    2   0.03  0.97
  9 0.120000 0.122364   1.97 0.00  5    1   0.06  0.94
 10 0.123540 0.124519   0.79 1.00  8    2   0.04  0.96
 11 0.129425 0.129080  -0.27 1.00  8    3   0.28  0.72
 12 0.130000 0.131401   1.08 0.00  5    2   0.19  0.81
 13 0.133520 0.133260  -0.19 1.00  2    3   0.32  0.68
 14 0.140097 0.139899  -0.14 1.00  5    3   0.24  0.76
 15 0.148000 0.148323   0.22 0.00  7    3   0.46  0.54
 16 0.151591 0.151241  -0.23 1.00  1    3   0.51  0.49
 17 0.152000 0.152678   0.45 0.00  8    4   0.04  0.96
 18 0.153721 0.154599   0.57 1.00  5    4   0.59  0.41
 19 0.158010 0.157285  -0.46 1.00  3    3   0.35  0.65
 20 0.157000 0.160485   2.22 0.00  5    5   0.66  0.34
 21 0.160894 0.164467   2.22 0.00  4    3   0.16  0.84
 22 0.165000 0.165694   0.42 0.00  6    4   0.24  0.76
 23 0.166703 0.166526  -0.11 1.00  2    4   0.05  0.95
 24 0.169262 0.169472   0.12 1.00  1    4   0.09  0.91
 25 0.169000 0.170025   0.61 0.00  7    4   0.14  0.86
 26 0.174689 0.175553   0.49 0.00  7    5   0.31  0.69
 27 0.177014 0.176657  -0.20 1.00  1    5   0.36  0.64
 28 0.183327 0.183073  -0.14 1.00  5    6   1.32 -0.32
 29 0.185536 0.183618  -1.03 1.00  3    4   0.01  0.99
 30 0.185536 0.186166   0.34 0.00  6    5   0.10  0.90
 31 0.190223 0.190978   0.40 1.00  1    6   0.22  0.78
 32 0.194413 0.194224  -0.10 1.00  6    6   0.11  0.89
 33 0.197207 0.197450   0.12 1.00  3    5   0.33  0.67

Bulk Modulus=    0.0581

   c11      c22      c33      c23      c13      c12      c44      c55      c66
 0.12214  0.12214  0.12214  0.02608  0.02608  0.02608  0.04803  0.04803  0.04803

   d1       d2       d3
  0.91191  0.82873  0.68628

 loop# 5   rms error=  0.4430 %, changed by 0.0000000 %

 length of gradient vector=  0.000002   blamb=   0.000000

 eigenvalues           eigenvectors
      88.96410     1.00  0.08
    2149.01643    -0.08  1.00

chisquare increased 2% by the following % changes in independent parameters
  0.32  -0.07
  0.01   0.16
```

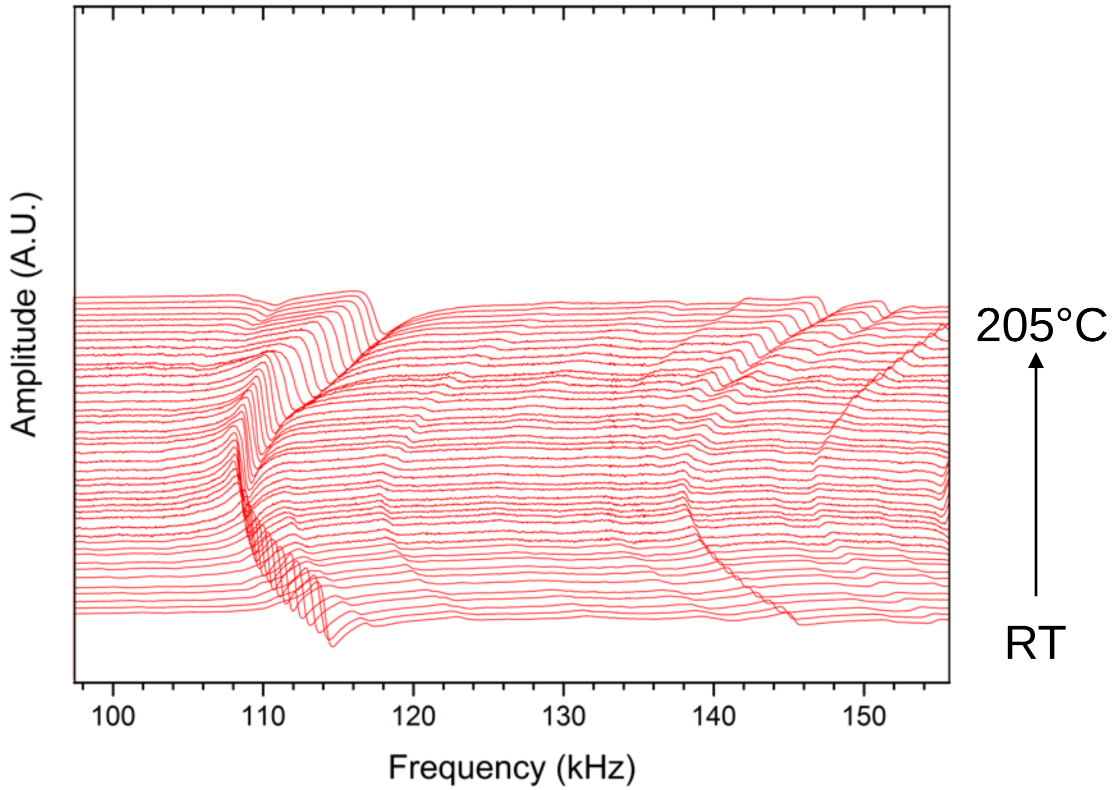
Experimental



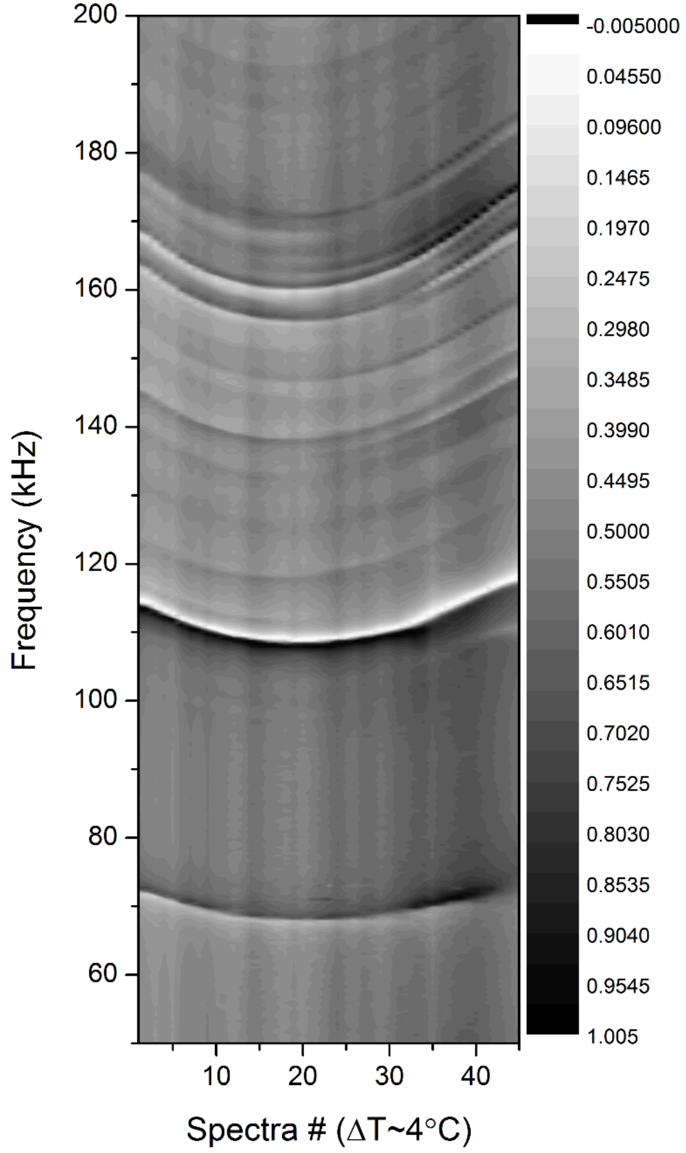


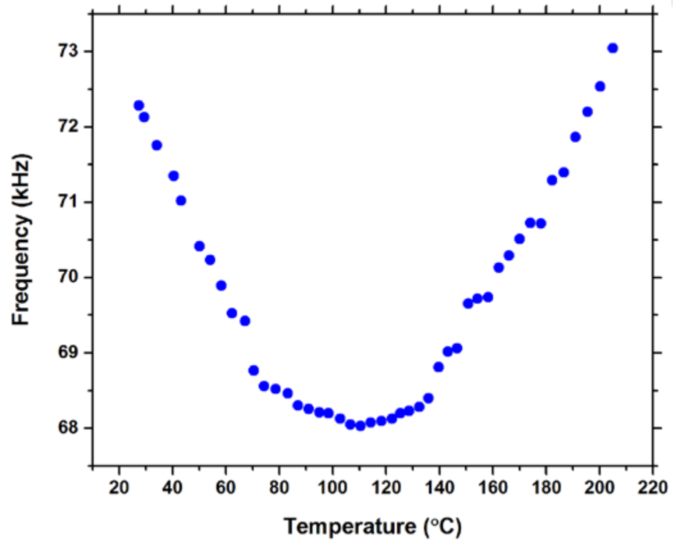
Results

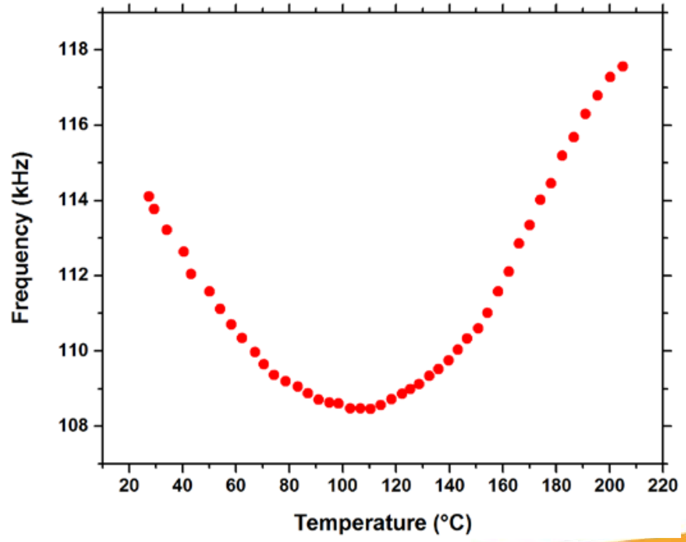
- Focus was on temperature dependence of elastic properties of Berea Sandstone
- Waterfall plot → anomalous elastic behavior (i.e. softening with cooling)
- This indicates a complex mechanical phenomenon happens with decreasing temperature in Berea sandstone
- The data have been confirmed with separate experimental techniques (Pitch-Catch)



Results







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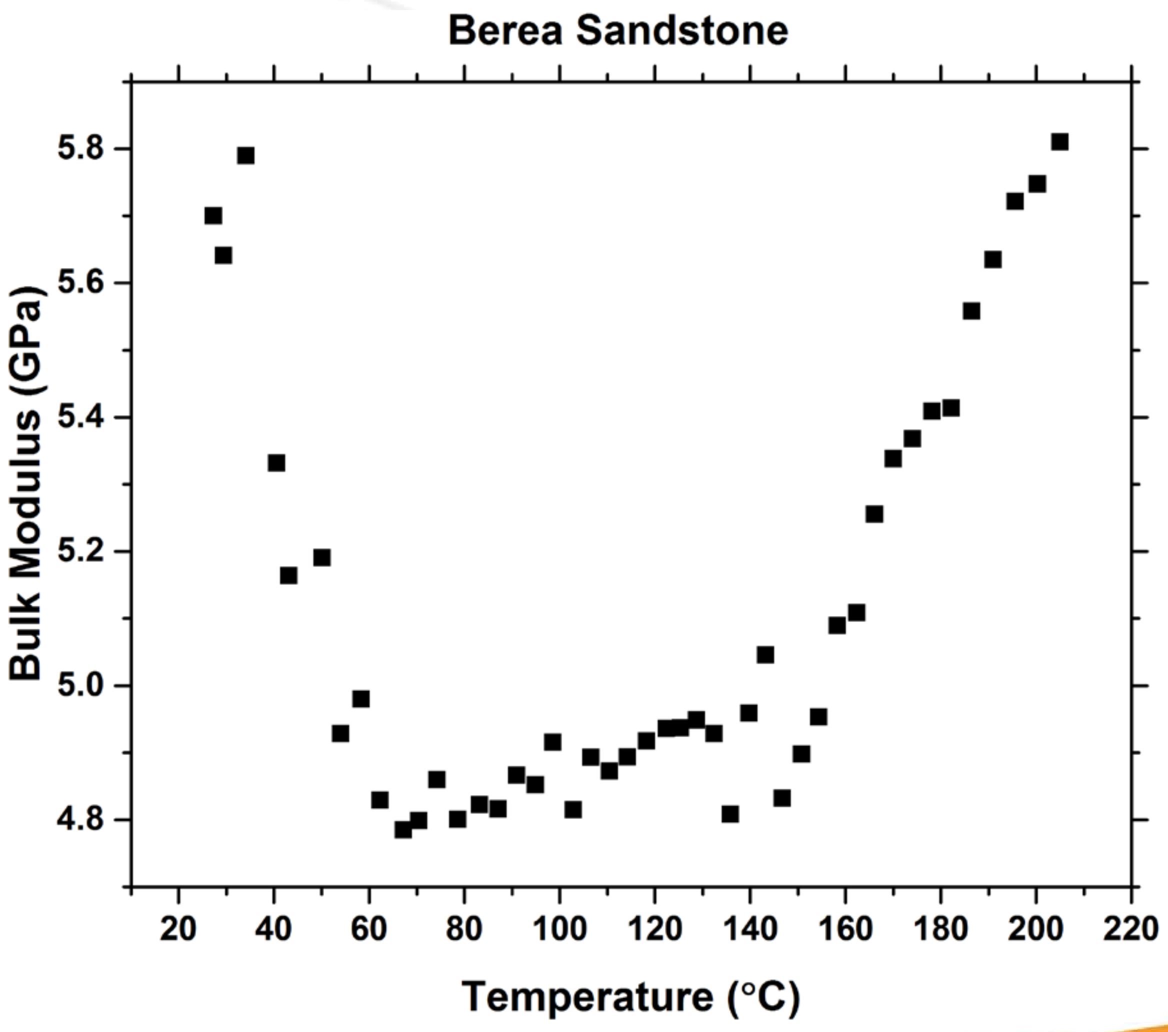
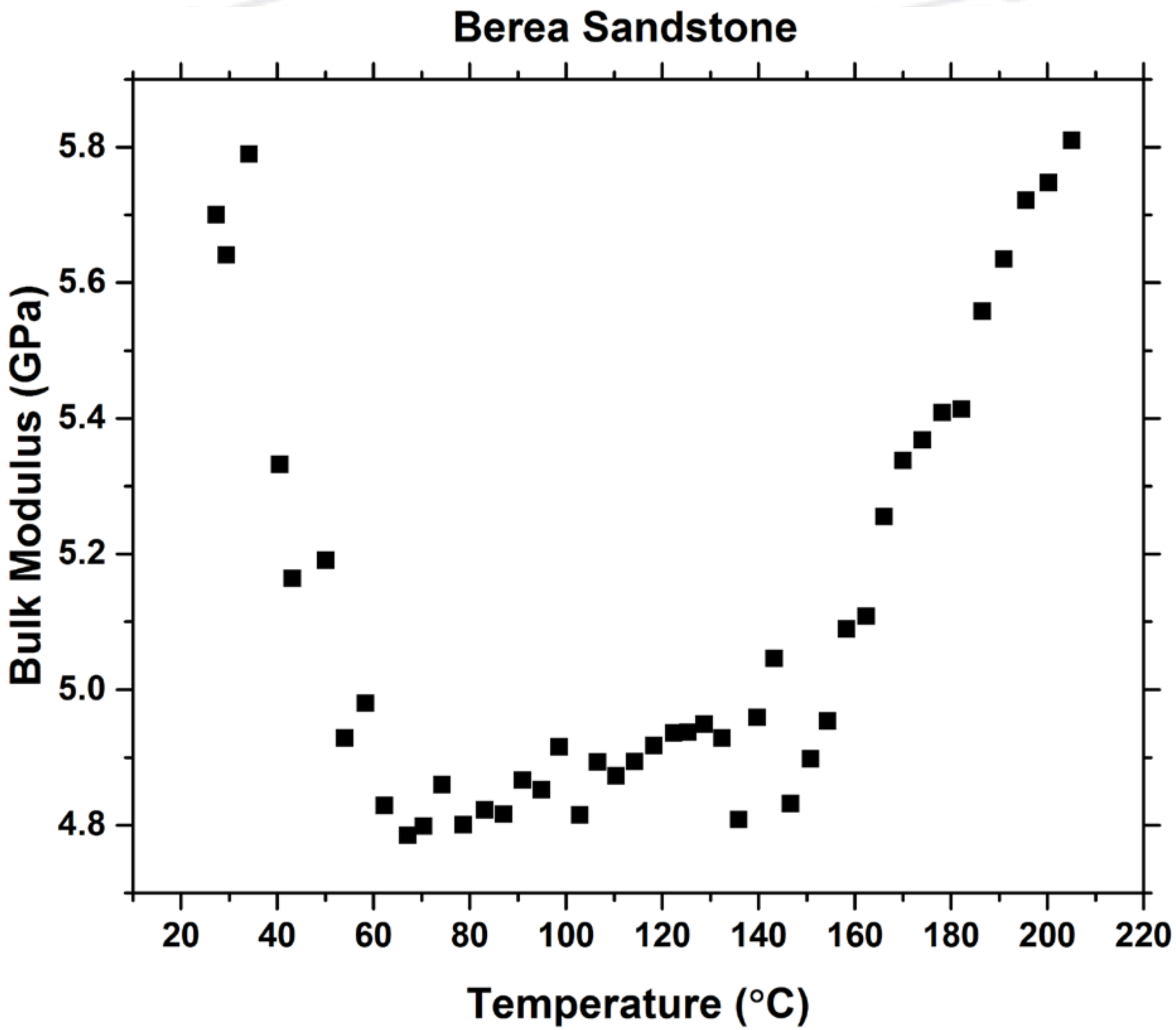
Results

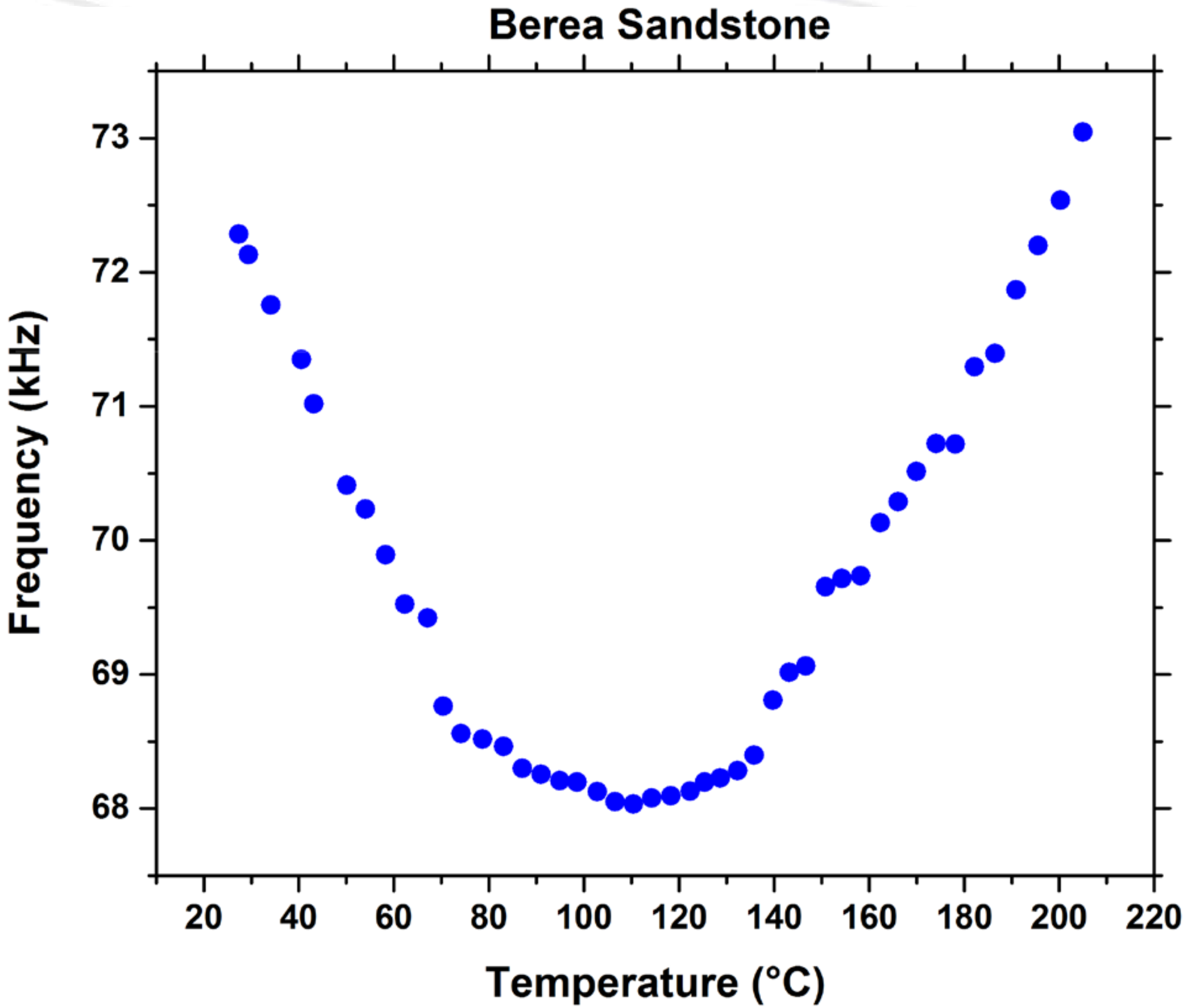
- After fitting and data analysis, bulk modulus follows the same trend
- Temperature appears to significantly affect the mechanical properties of Berea
- Extracting the bulk modulus is time intensive
- For qualitative analysis, it is better (easier, faster) to investigate resonance shifting



Results



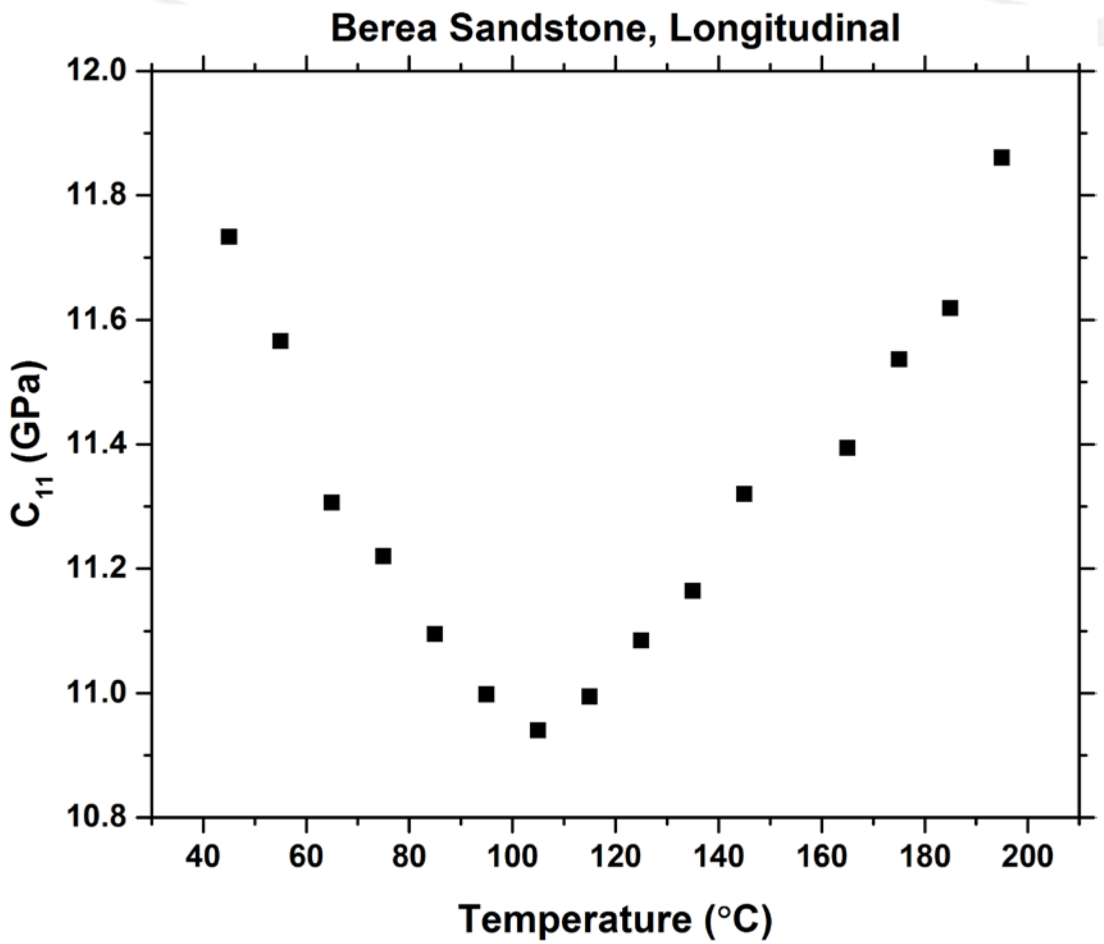
Berea bulk modulus vs temperature



Berea frequency shifting vs temperature

Results

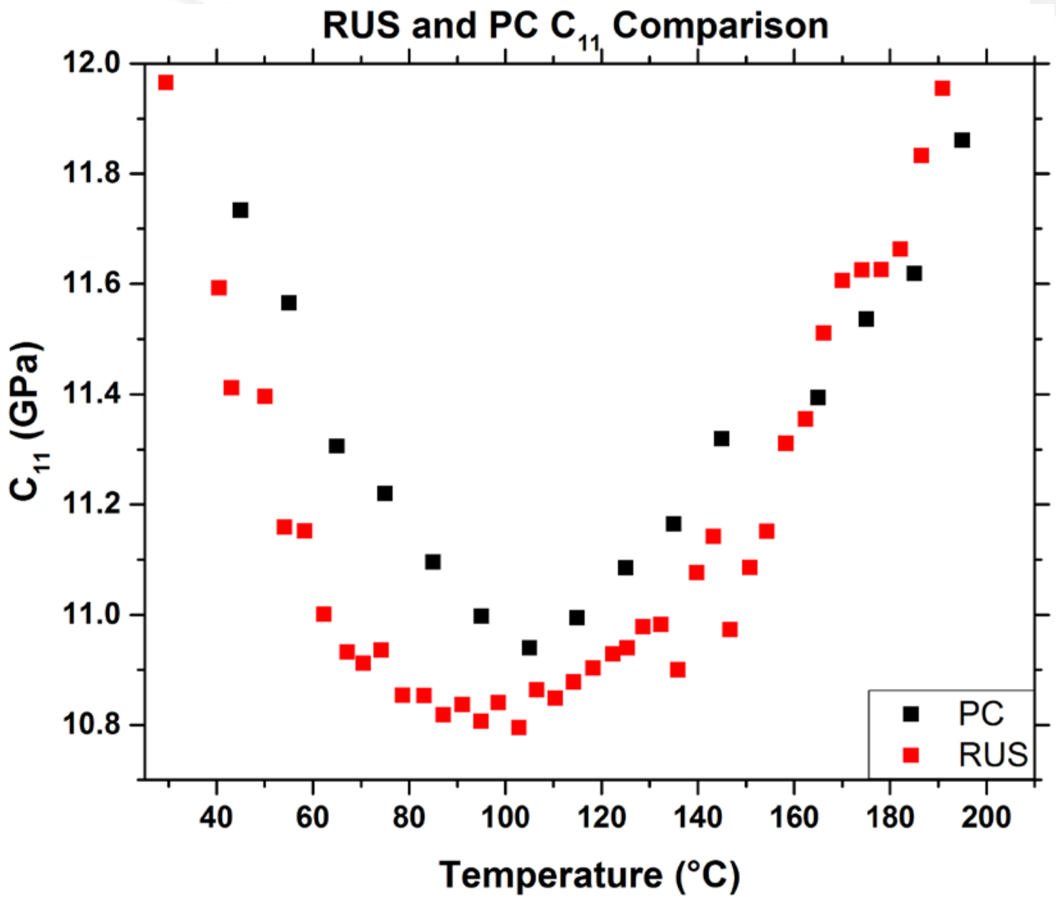
- To confirm the results, we use Pitch-Catch technique
- We measure ToF, path length, to determine elastic constants and bulk modulus
- New samples with different dimensions are used
- 2 sets: One with shear transducers and one with longitudinal
- Both sets confirm previous RUS results



Results

- Comparison of RUS and PC C_{11} results show good agreement

- Similar qualitative behavior was observed from both types of experiments



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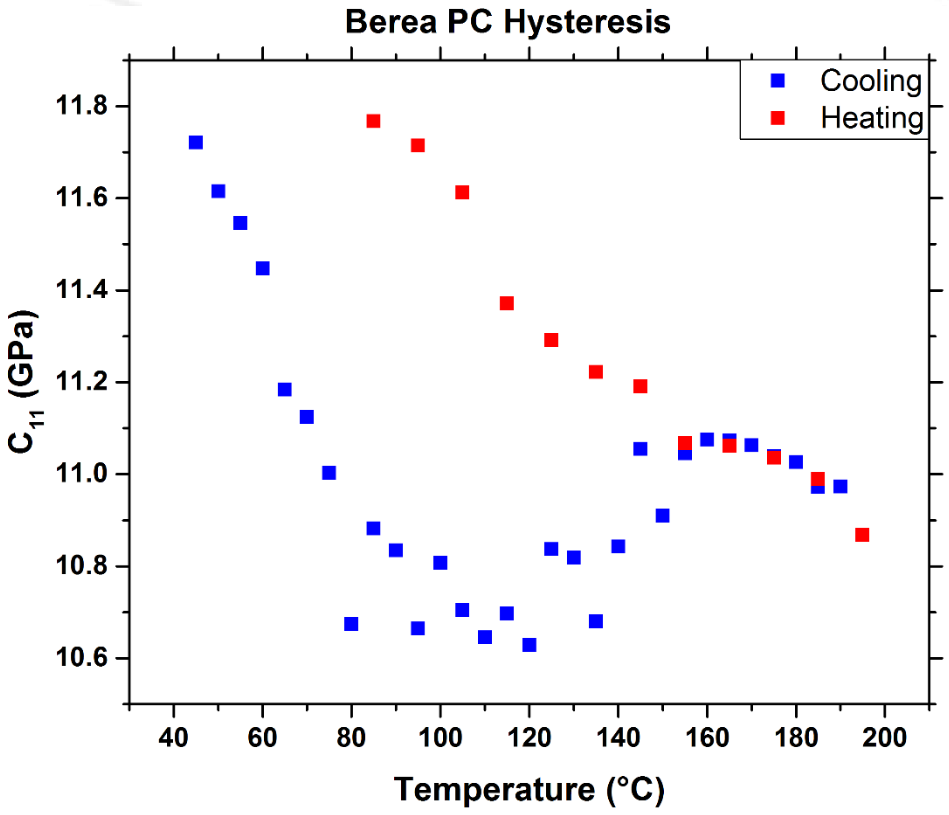
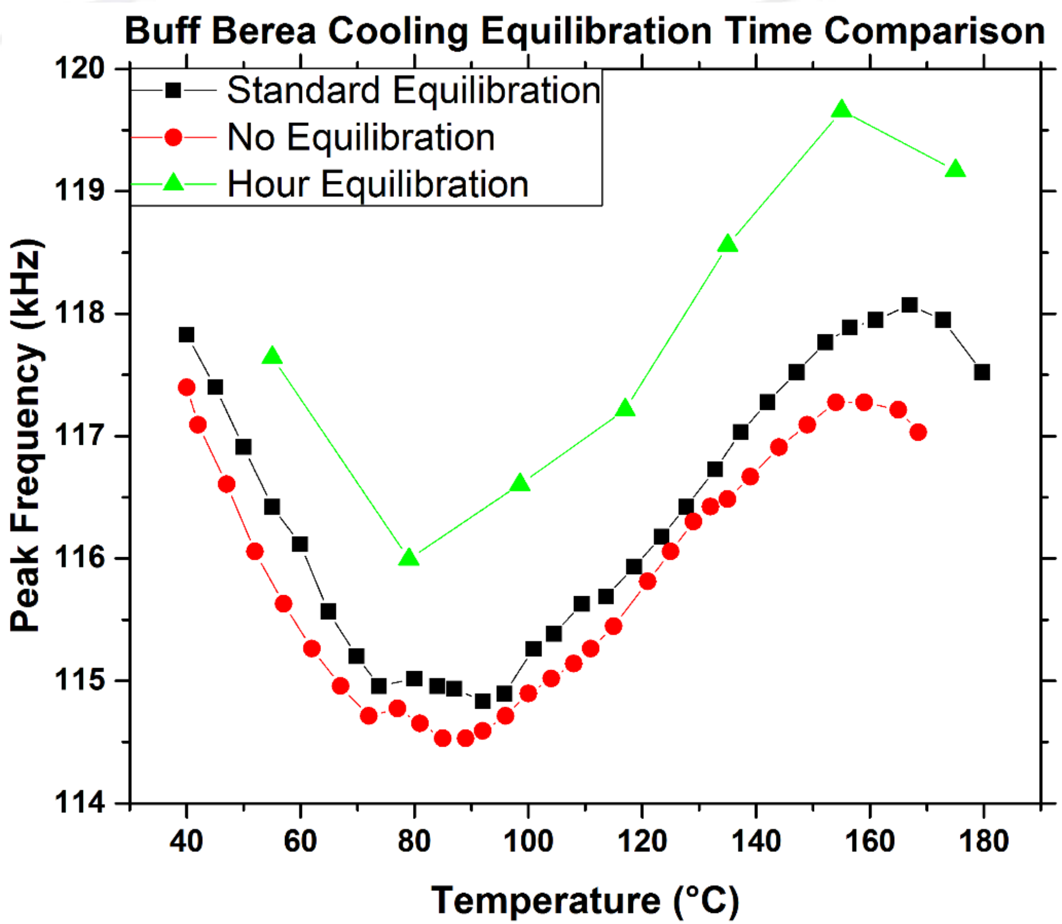
Results

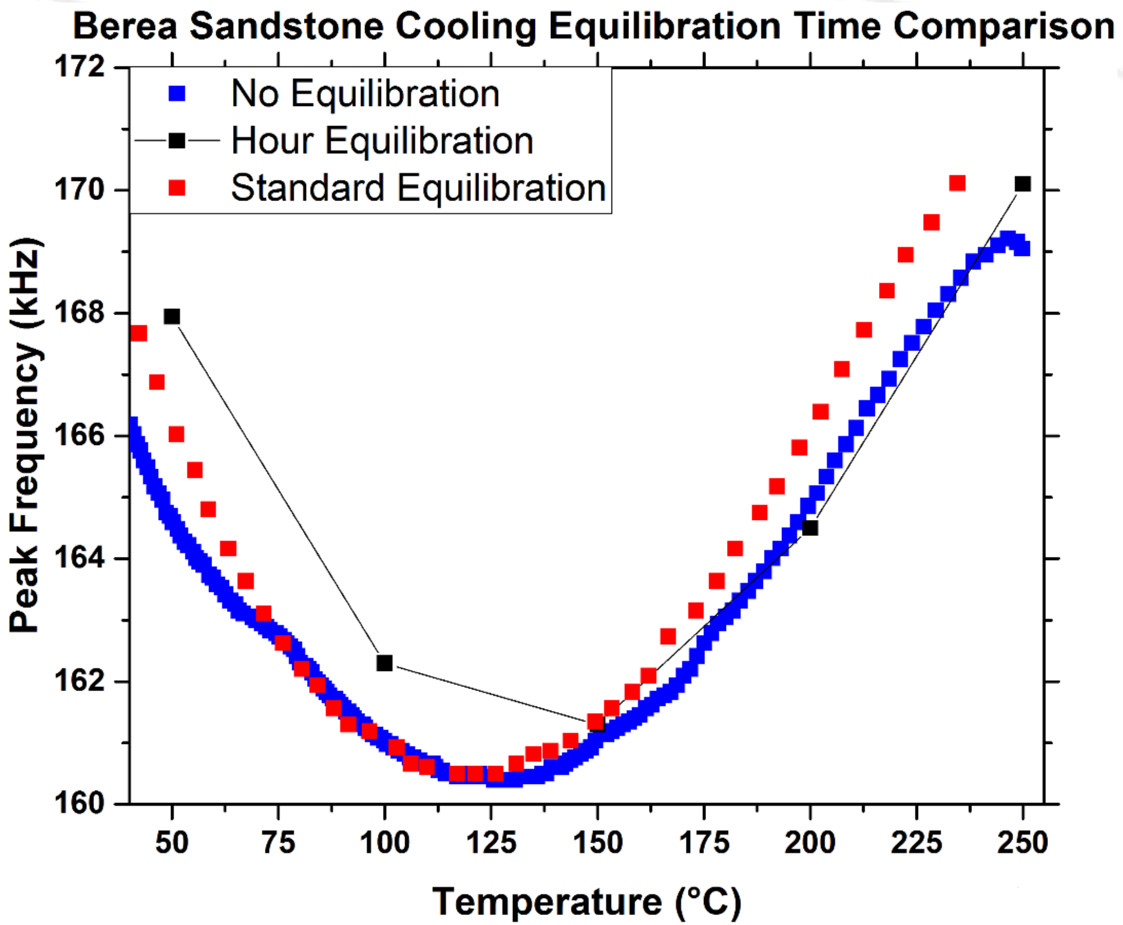
- Anomalous behavior believed to be associated with strain-driven slow dynamics (Ref 1-3).
- Investigated hysteresis curves to determine if the anomalous behavior extends to heating as well
- Different behavior (normal) observed for heating
- Repeated cycling shows similar behavior
- Same trend observed in both shear and longitudinal experiments



[1]Johnson, P. A., R. A. Guyer, and L. A. Ostrovsky (1999), A nonlinear mesoscopic elastic class of materials, AIP Conf. Proc., 524, 291–294, doi:10.1121/1.427349.
[2]Ten Cate, J. A., and T. J. Shankland (1996), Slow dynamics in the nonlinear elastic response of Berea sandstone, Geophys. Res. LePC., 23, 3019–3022, doi:10.1029/96GL02884.
[3]Ulrich, T. J., and T. W. Darling (2001), Observation of anomalous elastic behavior in rock at low temperatures, Geophys. Res. LePC., 28, 2293–2296, doi:10.1029/2000GL012480.

Results

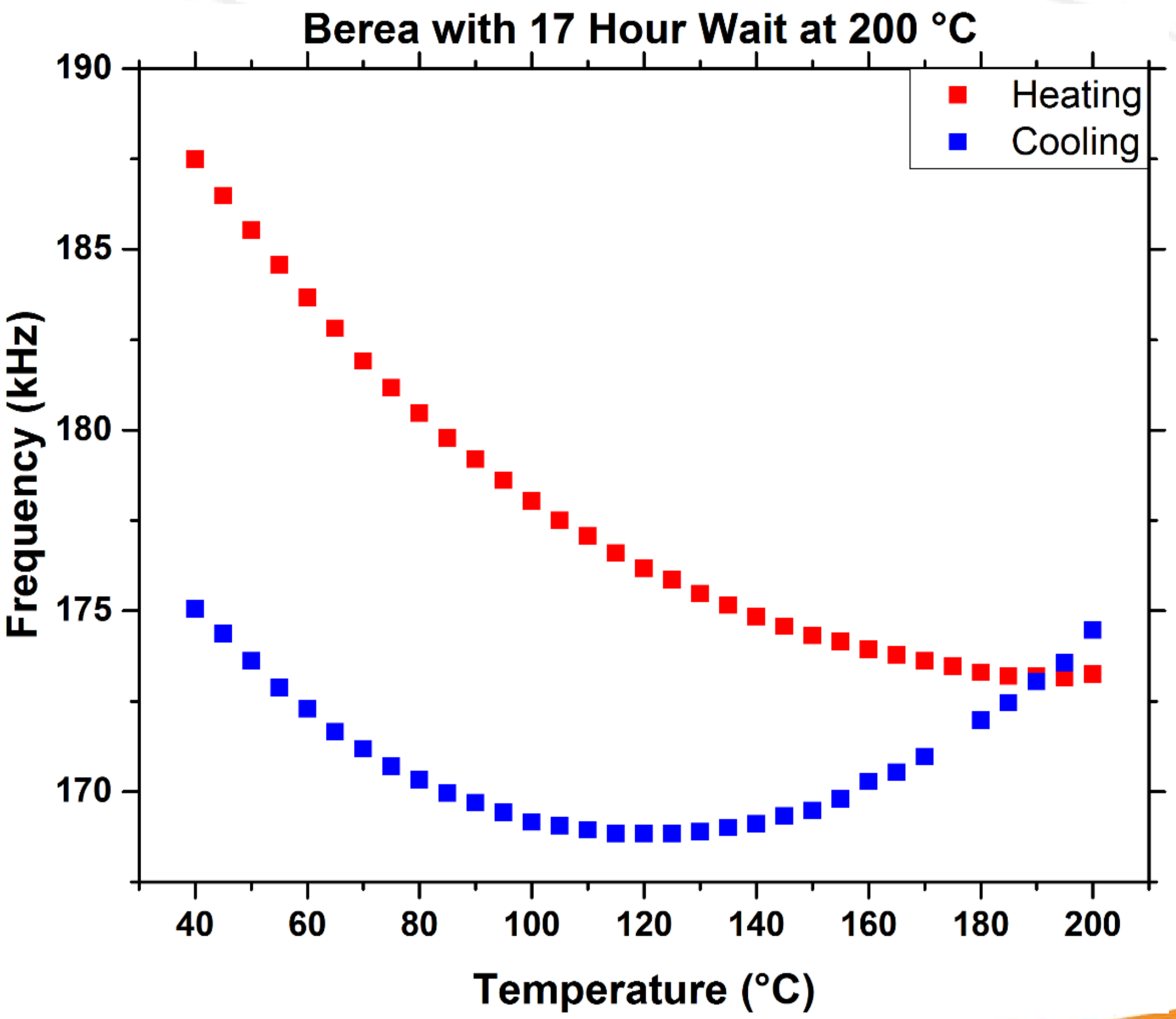




- Equilibration time in both Berea and Buff Berea does not appear to make a difference
- Unlikely to be a long-lasting relaxation mechanism?

Results

- Allowing the sample to relax at the highest temperature after heating has the effect of further separating the heating and cooling curves at low temperatures
- The qualitative behavior remains the same for both curves but they do not close at the lowest temperature
- Waiting significant amounts of time at different temperature steps has the effect of shifting the spectrum rather than changing the underlying behavior
- A small discontinuity can be seen at the highest temperature before the cooling curve is started



Conclusions

- Anomalous elastic behavior was found in Berea sandstone and Buff Berea when cooled from higher temperatures
- This behavior was confirmed with both RUS and PC
- The elastic behavior is normal with heating but abnormal with cooling, creating a hysteresis curve with temperature
- Equilibration time at each temperature step did not seem to be a factor affecting the anomalous behavior, possibly indicating that it is not caused by long term relaxation
- More investigation will be necessary to pinpoint the exact cause of this behavior